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A CURRENT PREDICTION OF THE ICF GAIN CURVE, ITS UNCERTAINTIES, AND IMPLICATIONS FOR ICF STRATEGY†

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ABSTRACT

We present our gain predictions for indirect-drive ICF targets, based on current target physics knowledge. In order to understand the uncertainties involved in predicting the performance of future ICF targets, we have constructed a simple model that contains a few basic features of target operation and estimates the possible effects of other complex target processes via simple parametrizations. We evaluate the scalings and uncertainties in the model parameters using current data, detailed calculations, and estimates of some of the underlying target physics processes. We present Monte-Carlo calculations with this model showing the propagation of the estimated uncertainties to the "near-ignition" and "high-gain" regimes. We estimate the probability of success as a function of required target gain and available driver energy, and illustrate using some current facility-planning scenarios. We discuss the role of potential future experiments in constraining currently-uncertain theoretical models.

We have developed a new method for predicting the ICF gain curve, based upon the current experimental and calculational target physics database. We constructed a target-gain model framework that parametrizes the efficiency or gain scaling of the key target physics processes for indirect-drive targets. We then analyzed the current ICF target physics database to estimate scalings and uncertainties for each efficiency and gain in the model. We include information gleaned from data points, extrapolations of data points, optimized LASNEX design calculations, LASNEX calculations using developmental models, and, where necessary, theoretical estimates and technical judgement. The methodology makes obvious the areas of missing experimental information, important physics complexities, and the largest target design inefficiencies and uncertainties. The result is a quantitative, probabalistic gain curve, based on current knowledge, that can be used to evaluate and plan ICF facility strategies.

For this work, we focus on Hydrodynamically-Scaled Targets (HST's), *i.e.*, targets that evolve hydrodynamically like current high gain ICF target designs. Key features of such high-performance, single-shell, spherical capsules are the simultaneous formation of a hot-spot and a low-entropy fuel layer, their radial convergences, and the inflight aspect ratio as the shell implodes. High-performance hohlraums must provide efficient overall coupling of the laser light energy to x ray drive at the capsule ablator, while providing the required x ray flux, spectrum, time dependence, and spatial symmetry to achieve the desired capsule implosion, and avoiding deleterious levels of hot electron production and preheat due to plasma instabilities.

The performance of an indirect drive ICF target can be conceptually factored into two major blocks, the hohlraum coupling efficiency, and the capsule gain, as shown schematically in Fig. 1. We discuss the capsule gain and hohlraum coupling models next, in turn.

The capsule gain model describes three regimes of ICF capsule operation (Fig. 2): pre-ignition, bootstrapping, and high-gain. Key aspects of ICF capsule design/physics include details of zero-order hydrodynamics (such as coupling of the radition drive to the ablator, ablation rate and pressure, and density gradient), precise drive pulse shaping to establish the required hot-spot and low-entropy main fuel, the radial convergences of the hot-spot and main fuel, tolerance to drive asymmetries, and the initiation, growth, and effects of fluid instabilities, turbulence, and mix. These processes are taken into account, at the current state-of-the-art, with detailed LASNEX[1] modeling. The capsule gain model's six adjustable parameters and their uncertainties are set using constraints available from LASNEX calculations and data from Centurion/Halite and Nova capsule tests. The Centurion/Halite program has performed ICF experiments using nuclear explosives at the Nevada Test Site. The Nova laser at LLNL has extensively tested ICF indirect-drive targets at drive energies up to about 20 kJ with simple pulse shapes,[2] and has recently begun to perform experiments at higher target energies and with more sophisticated pulse shapes.[3] To date, Nova capsules imploded at higher convergence ratios have been significantly degraded, compared with 1-D calculations, perhaps by effects of asymetric drive and pusher/fuel mixing. This fact and the uncertainty associated with extrapolating from currently-tested capsule conditions to those of megajoule-scale HST's contribute significantly to the current uncertainty in the capsule gain curve.

The hohlraum coupling efficiency is subdivided for modeling convenience into five specific coupling processes: (useful) laser light absorption, effects of Laser-Plasma Instabilities (LPI's), conversion of laser light to x-rays, x-ray losses, and coupling of symmetric drive to the capsule. The overall hohlraum coupling efficiency is the product of individual efficiencies determined for each coupling process. Each process efficiency is evaluated from the current database of LASNEX calculations, theoretical calculations and estimates, and laser experiments. Most of the efficiencies are parametrized to scale logarithmically with target drive energy. The one exception is that the effects of laser-plasma instabilities are represented by an efficiency that scales with a threshold behavior as a function of drive energy. We consider plasma processes that are growing convectively, *i.e.*, that grow exponentially as the (normalized) plasma scalelength increases. We assume the plasma size and scalelength vary with laser energy and pulse duration according to hydrodynamic scaling, *i.e.*, $L \sim \tau \sim E^{1/3}$. The "efficiency" for plasma processes represents the energy penalty that would be incurred to redesign the target to obtain tolerable hot electron preheat levels. At low laser energies, the model assumes no penalty due to LPI's, consistent with Nova data and theoretical estimates for small HST's. At higher energies, the model uses a threshold function with adjustable location, height, and onset slope, and assumes that the efficiency penalty is constant after LPI saturation. The lowest single process efficiency is that associated with drive symmetrization. Uncertainties are most significant for predictions of drive symmetrization and LPI's. In fact, the effects of LPI's are difficult to predict in closed form, and only estimates are possible.

The current x ray conversion database[4] is an example of how available data constrains the model efficiencies. Current measured x ray conversion efficiencies (XCE) using gold disks and spheres are in the range of 50-90%. Two important data trends are particularly relevant: a general scaling toward higher XCE with lower $I\lambda^2$ and a significant improvement in conversion with improved illumination uniformity. Calculated scaling with plasma scalelength (hence, drive energy) is quite weak.[5] Less well-known, experimentally, are the scalings with pulse duration and shape.

Once the model parameters and uncertainties have been set, based on the available target physics database, a Monte Carlo calculation allows evaluation of overall target gain probabilities. The result, Fig. 3, is a prediction for target gain *vs.* laser drive energy, based on our analysis of current target physics knowledge. The contours shown are labelled by their associated probabilities, *i.e.*, the probability of exceeding the plotted gain. As a benchmark, we show the data point derived from several tests of a particular gas-fueled (non-HST) Nova target design, together with its experimental uncertainty (shaded box) and the estimated total uncertainty including the extrapolation to HST conditions (hatched bar).

Using this model, we can estimate the effects of future experiments on the shape and uncertainty of the ICF gain curve. Fig. 4 shows the current gain curve prediction, together with the gain curves that would result from successful experiments demonstrating HST's using 100 kJ or 1 MJ laser facilities. For these calculations, "success" was defined as verifying target performance at the $+1\text{-}\sigma$ level of the current prediction.

Our gain-curve prediction allows quantitative answers to facility-planning hypotheses, based on current target physics knowledge. For example, there is high (90%) confidence of achieving over 100 MJ yield using an appropriate 60 MJ laser driver, a strong indication of the scientific feasibility of ICF. Precision indirect-drive ICF experiments at 100 kJ and 1 MJ could substantially reduce the levels of predictive uncertainties. Further, we find that successful HST experiments at 1 MJ laser energy could reduce the predicted required driver energy to 10 MJ or below.

Future extensions of this work should be valuable. Applying this methodology to direct-drive ICF could provide a fair, quantitative assessment of that target approach. Also, as the target physics database grows and inventions occur, improvements and updates of this analysis can track progress toward the ultimate goals of ICF.

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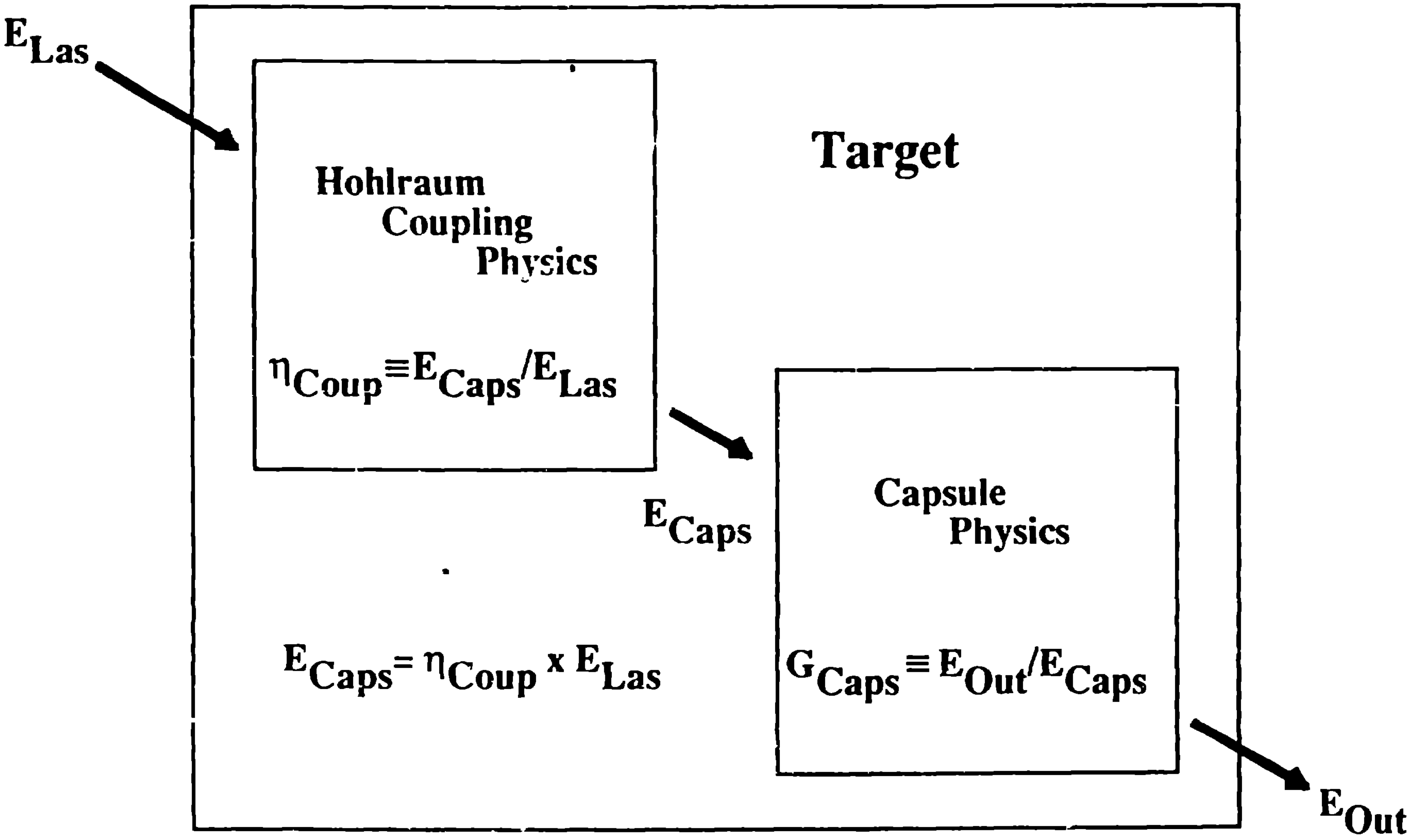

$$G_{Targ} \equiv E_{Out}/E_{Las} = \eta_{Coup} \times G_{Caps}$$

Figure 1. Performance of an ICF Indirect-Drive target can be factored into two major blocks.

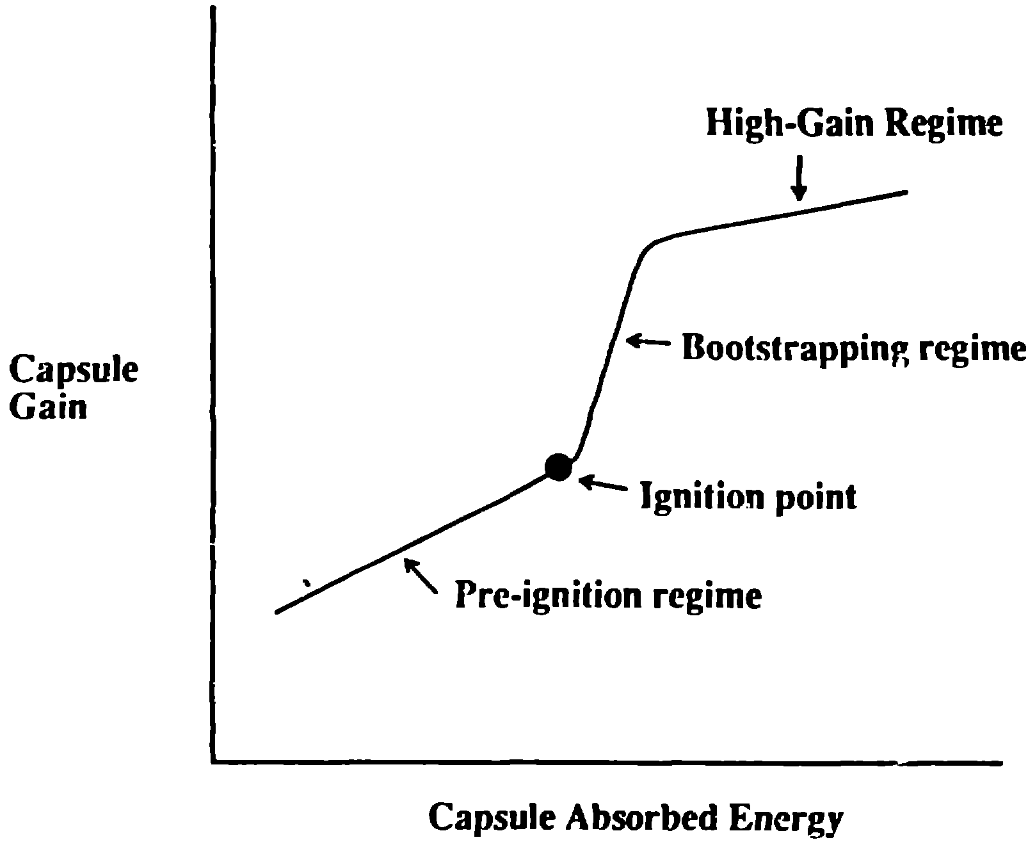

Figure 2. Capsule gain model has basic causality and parametrizes capsule operating regimes.

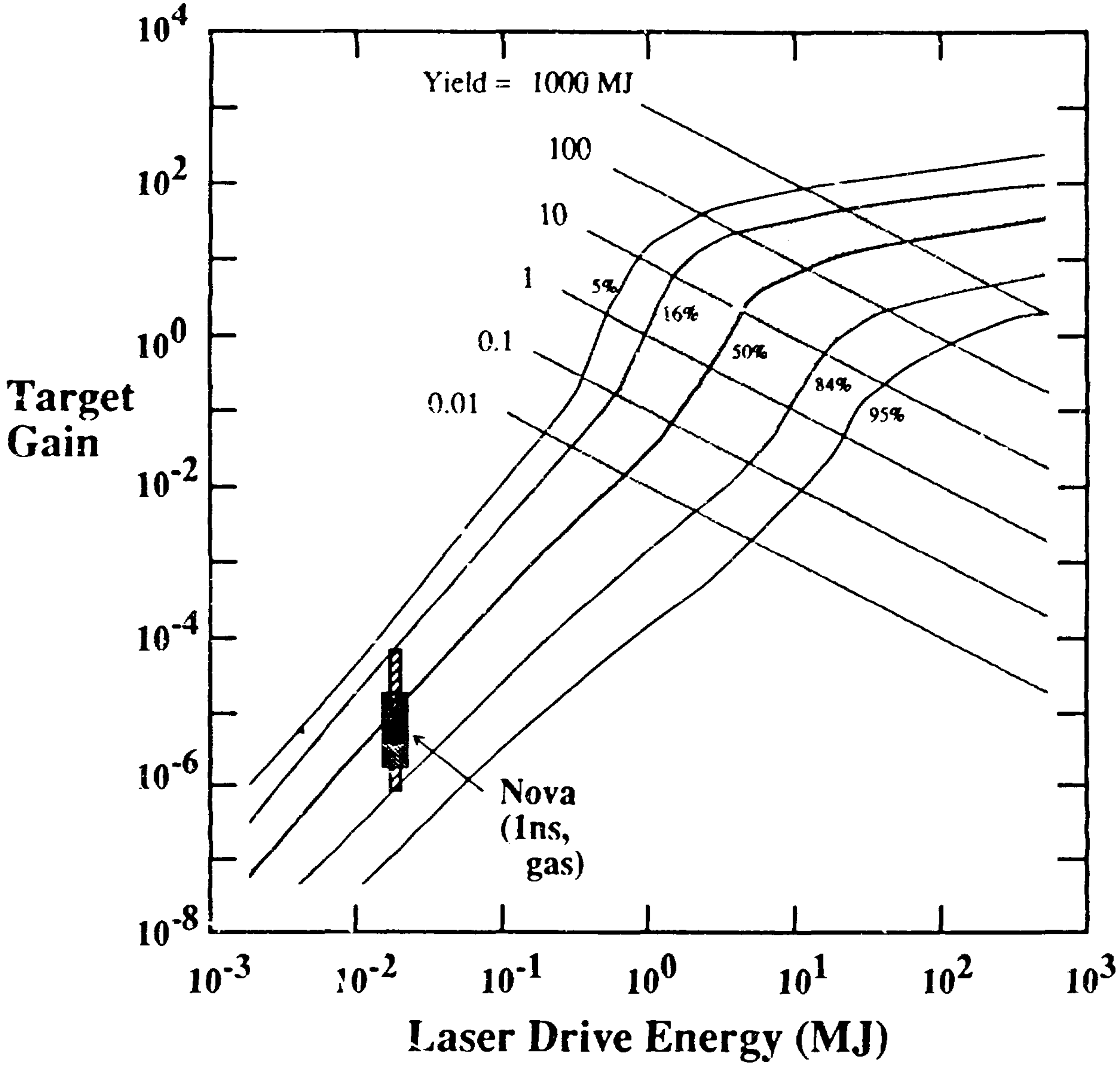

Figure 3. Predicted gain curve for Hydrodynamically-Scaled Targets has large uncertainties that result from remaining target physics issues.

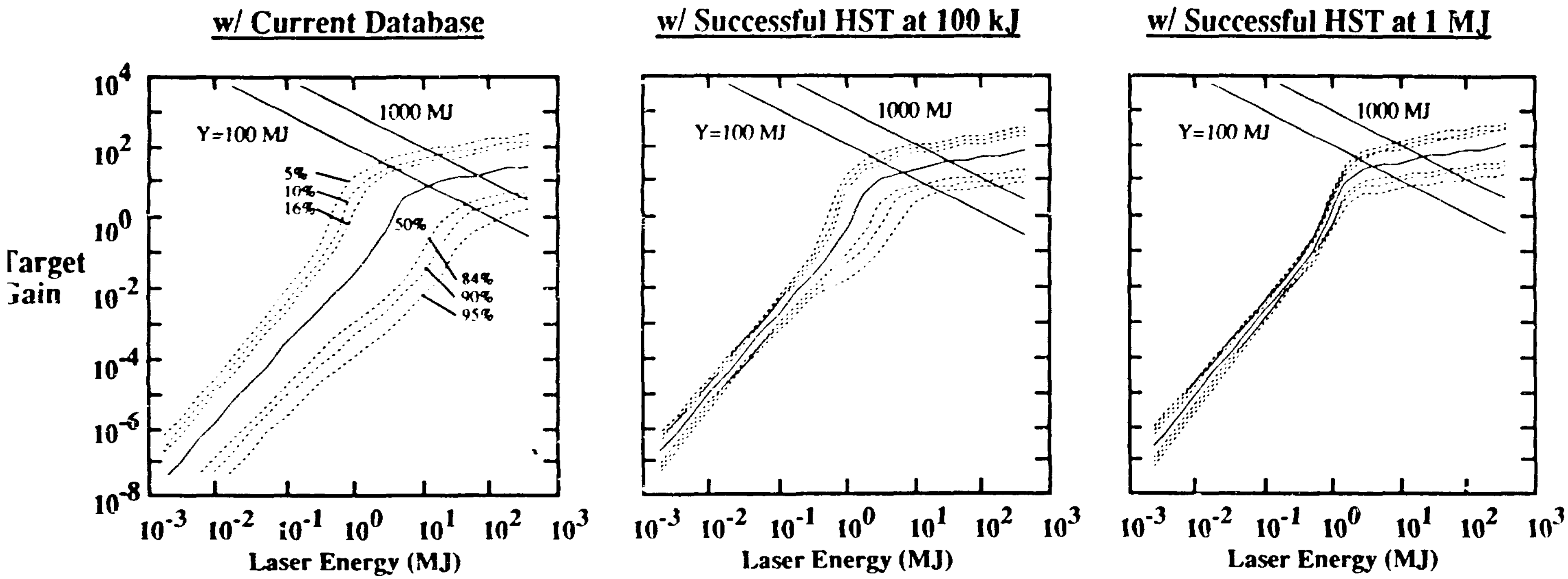

Figure 4. Experiments with Hydrodynamically-Scaled Targets will reduce gain-curve uncertainties, and may redefine its shape and location.